

Kentucky Geological Survey
University of Kentucky, Lexington

An Update of Seismic Monitoring and Research in the Vicinity of the Paducah Gaseous Diffusion Plant: January 2013–December 2017

Zhenming Wang, Edward W. Woolery, and
N. Seth Carpenter

Our Mission

The Kentucky Geological Survey is a state-supported research center and public resource within the University of Kentucky. Our mission is to support sustainable prosperity of the commonwealth, the vitality of its flagship university, and the welfare of its people. We do this by conducting research and providing unbiased information about geologic resources, environmental issues, and natural hazards affecting Kentucky.

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Technical Level



Statement of Benefit to Kentucky

Continuing efforts to monitor earthquakes and conduct research have enhanced our understanding of seismic hazards in western Kentucky, which in turn has contributed to a sound scientific basis for developing design ground motions for buildings and facilities in western Kentucky, in particular at the Paducah Gaseous Diffusion Plant.

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Contents

Abstract.....	1
Introduction	1
Seismic and Strong-Motion Network Operation and Data Analysis.....	2
Seismic-Data Analysis.....	3
Analysis of CUSSO and VSAP Data.....	4
Seismic-Hazard Assessment and Communication.....	5
New Madrid Active Faults.....	5
Ground-Motion Attenuation.....	6
Seismic-Hazard Assessment.....	8
Potential Loss Estimate and Mitigation Policy.....	13
Summary	16
References Cited.....	16

Figures

1. Map showing locations of seismic and strong-motion stations operated in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017.....	3
2. Map showing locations of earthquakes occurring in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017	4
3. Example recordings by the seismic-monitoring network.....	6
4. Chart summarizing CUSSO's operational history	7
5. Recordings at VSAP and CUSSO showing mean spectral ratios and theoretical Thomson-Haskell SH-wave transfer functions	8
6. Map showing locations of the active faults in the New Madrid Seismic Zone used in the USGS national seismic-hazard maps.....	8
7. Map illustrating seismicity, active faults, topography, and geologic features in the New Madrid Seismic Zone.....	9
8. Two seismic-reflection soundings	10
9. Map showing top of the Paleogene structure contoured as separate surfaces, south, within, and north of the Charleston Uplift, and cross section B-B'.....	11
10. Map showing Charleston Uplift and field locations.....	12
11. Maps showing stable continental regions of North America and South China	13
12. Graph comparing ground-motion predictions for the Sichuan Basin and four GMPEs for the central and eastern United States for an M7.9 earthquake	14
13. Map showing predicted peak ground acceleration on hard rock from a magnitude-7.5 scenario earthquake in the New Madrid Seismic Zone	15

Tables

1. Design ground motions for Paducah, San Francisco, and Los Angeles	2
2. Ground motions for Paducah estimated by the U.S. Geological Survey.....	2
3. Earthquakes of magnitude 3.0 and greater in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017	5
4. Earthquakes recorded at station VSAP between 2004 and 2014.....	7
5. Comparison of maximum ground motions for New Madrid scenario earthquakes.....	15

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Abstract

From January 2013 to December 2017, the Kentucky Geological Survey monitored earthquakes and conducted research on seismic hazards in the vicinity of the Paducah Gaseous Diffusion Plant, a former uranium enrichment facility, in western Kentucky. Fifteen earthquakes with magnitude greater than 3.0 occurred in the area during this period, and data were collected from the Central U.S. Seismic Observatory and the vertical seismic array at the gaseous diffusion plant. This monitoring improved our understanding of seismic-wave propagation through thick sediments and ground-motion site effects, as well as fault locations in the New Madrid Seismic Zone, ground-motion attenuation, and seismic-hazard assessment. Results have been communicated through publications and presentations at workshops and conferences. The data will contribute to the development of design ground motions for western Kentucky, and specifically for buildings and facilities at the Paducah Gaseous Diffusion Plant.

Introduction

Engineering seismic design became a major concern for the Paducah Gaseous Diffusion Plant, a former uranium enrichment facility in western Kentucky, when the 1997 National Earthquake Hazards Reduction Program Provisions (Building Seismic Safety Council, 1998) were adopted in the early 2000s. The design 0.2s response acceleration (PSA) in Paducah, Ky., was increased by about a factor of four, from 0.25 g in the 1994 edition of the provisions (Building Seismic Safety Council, 1995) to 1.083 g in the 1997 edition (Building Seismic Safety Council, 1998) (Table 1). This caused the U.S. Department of Energy to have difficulty obtaining a permit from federal and state regulators to construct a landfill at the plant in the early 2000s (James E. Beavers Consultants, 2010). The design values were developed from the ground motions with 2 percent probability of exceedance in 50 yr

produced by the U.S. Geological Survey (Frankel and others, 1996, 2002; Petersen and others, 2008, 2014). Table 2 shows that the ground motions for Paducah estimated by the USGS are higher than the design values (Table 1). These ground-motion estimates and resulting high design values have been an issue for the plant, as well as for western Kentucky in general.

In order to address the seismic-hazard assessment and engineering-design issues for the Paducah Gaseous Diffusion Plant, as well as for western Kentucky in general, the Kentucky Geological Survey, in conjunction with the University of Kentucky Department of Earth and Environmental Sciences, carried out comprehensive research with partial support from the U.S. Department of Energy through the Kentucky Research Consortium for Energy and Environment. Phase I of the research was from 2003 to 2007 and phase II was from 2009 to 2012. We installed and maintained a temporary

Table 1. Design ground motions for Paducah, San Francisco, and Los Angeles. *The value was obtained from the effective peak acceleration (A_g) $\times 2.5$. †The value (0.10) was the effective peak velocity-related acceleration (A_v).

NEHRP Recommended Provisions Edition	Paducah		San Francisco		Los Angeles	
	0.2s PSA (g)	1.0s PSA (g)	0.2s PSA (g)	1.0s PSA (g)	0.2s PSA (g)	1.0s PSA (g)
1994 (Building Seismic Safety Council, 1995)	0.25*	0.10†	1.00*	0.40†	1.00*	0.40†
1997 (Building Seismic Safety Council, 1998)	1.083	0.333	1.000	0.400	1.000	0.400
2003 (Building Seismic Safety Council, 2004)	1.000	0.333	1.000	0.406	1.386	0.468
2009 (Building Seismic Safety Council, 2009)	0.837	0.287	1.000	0.400	1.563	0.548
2015 (Building Seismic Safety Council, 2015)	0.672	0.223	0.900	0.320	1.165	0.369

Table 2. Ground motions for Paducah estimated by the U.S. Geological Survey.

Ground Motions With 2 Percent Probability of Exceedance in 50 Yr			
Year	PGA (g)	0.2s PSA (g)	1.0s PSA (g)
1996	0.826	1.566	0.463
2002	0.918	1.698	0.466
2008	0.754	1.423	0.412
2014	0.609	1.054	0.300

seismic network in the vicinity of the gaseous diffusion plant and analyzed the USGS probabilistic seismic-hazard maps and scenario ground-motion hazards. Phase I resulted in publications by Wang (2003, 2005, 2006, 2007, 2008), Wang and others (2003), Wang and Ormsbee (2005), Wang and Woolery (2006, 2008), and Woolery and others (2008). Phase II resulted in publications by Wang (2010, 2011), Wang and Lu (2011), Wang and Cobb (2012), Wang and others (2012), and Wang and Woolery (2013). The most significant outcomes from both phases are:

1. A better understanding of earthquake science and seismic-hazard assessment in western Kentucky and the central United States, resulting in a sound scientific basis for the development of design ground motions for buildings and facilities in the area.
2. Downward revision of the design ground motion to 0.33g PGA for a landfill at the plant, which allowed the Department of Energy to obtain permits from federal and state regulators to construct the landfill.
3. Revision of the Kentucky Residential Codes for western Kentucky, including Paducah.

4. Establishment of the Central United States Seismic Observatory.

This update summarizes the continuing research carried out by the Kentucky Geological Survey and UK Department of Earth and Environmental Sciences from January 2013 to December 2017.

Seismic and Strong-Motion Network Operation and Data Analysis

The Kentucky Geological Survey continued operation of the Kentucky Seismic and Strong-Motion Network in the vicinity of the gaseous diffusion plant between January 2013 and December 2017. Figure 1 shows the current station and instrumentation configuration, which focuses on monitoring in the New Madrid Seismic Zone. Seismometers for detecting seismic events are in operation at seven of the stations and at least one strong-motion sensor is in operation at 10 stations. Recordings from five of the stations are telemetered to KGS over the internet; the remaining stations are stand-alone, and are visited approximately bimonthly to download recordings. These stations, particularly the seismic stations, record earthquakes on local and global scales. The real-time recordings are shared

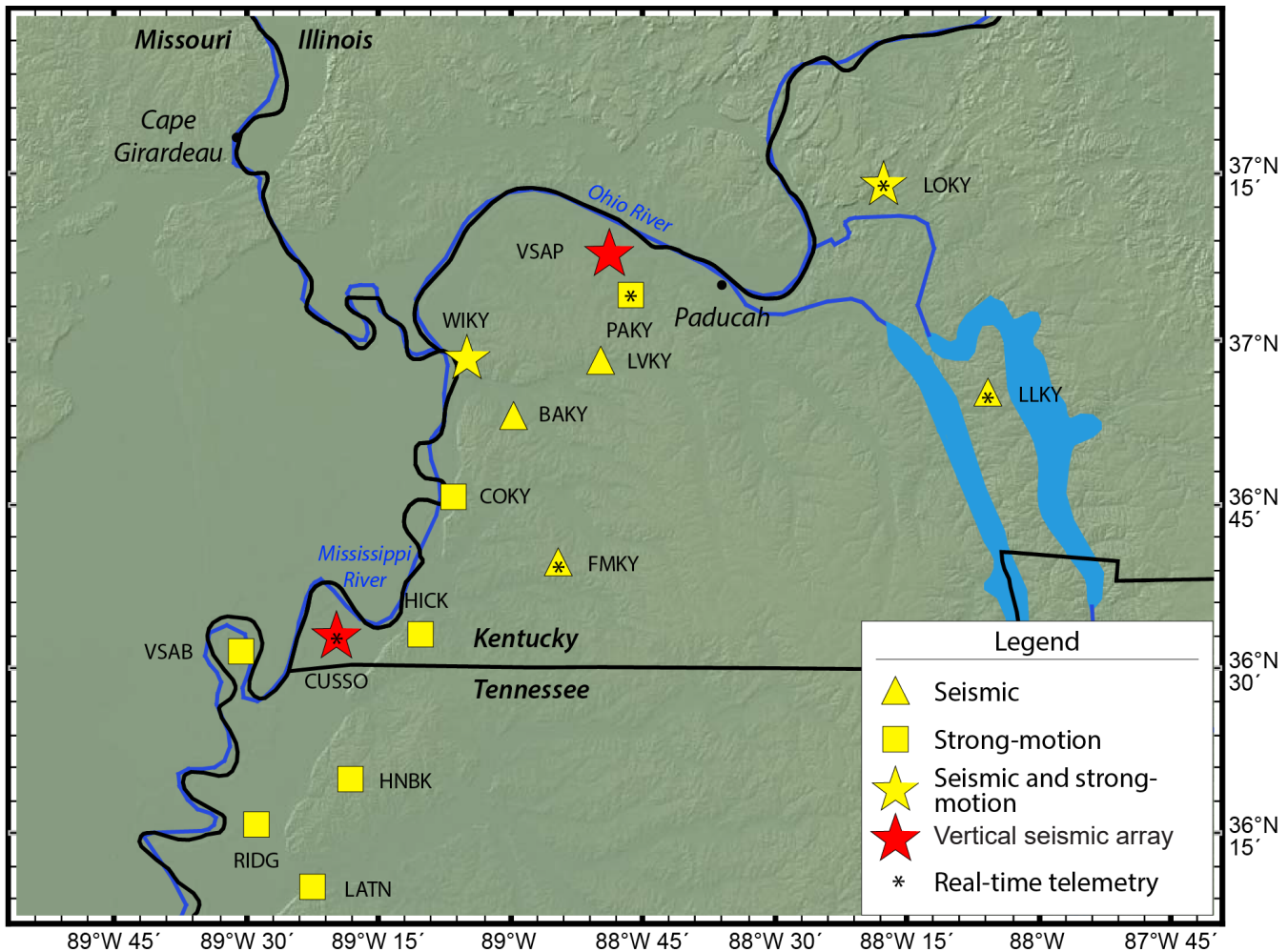


Figure 1. Seismic and strong-motion stations operated in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017. Kentucky Seismic and Strong-Motion station VSAP is located at the plant.

with the neighboring seismic-monitoring network operated by the University of Memphis.

Since 2013, all but one of the telemetered seismic stations have been upgraded with on-site digital data acquisition systems, including PAKY (Paducah Airport), FMKY (Fulgham, Ky.), and LOKY (Salem, Ky.). Strong-motion accelerometers were installed at PAKY and LOKY. All but two of the stations deployed in the Jackson Purchase Region of Kentucky as part of the temporary seismic-monitoring project in the vicinity of the Paducah Gaseous Diffusion Plant (Wang and Woolery, 2013) were removed prior to 2013. Of the remaining two stations, LVKY (Lovelaceville, Ky.) was removed in April 2013 and BAKY (Bardwell, Ky.) continues to operate.

Operation of several stations has been interrupted because of local site issues. The vertical

seismic array sites, VSAP and CUSO in particular, are discussed in the subsequent section. VSAB was flooded in 2013, and plans are to relocate it on higher ground. PAKY was struck by lightning in 2017 and is undergoing repair.

Seismic-Data Analysis

The recordings from the seismic stations in the vicinity of the gaseous diffusion plant (Fig. 1) were analyzed in tandem with recordings from nearby regional seismic stations operated by other agencies to determine the source parameters of local-area earthquakes. Figure 2 shows the locations of earthquakes with magnitude greater than 1.0 that occurred in the vicinity of the plant from January 2013 to December 2017. Information on the 15 earthquakes of magnitude 3.0 and greater during this period is listed in Table 3. The earthquake clos-

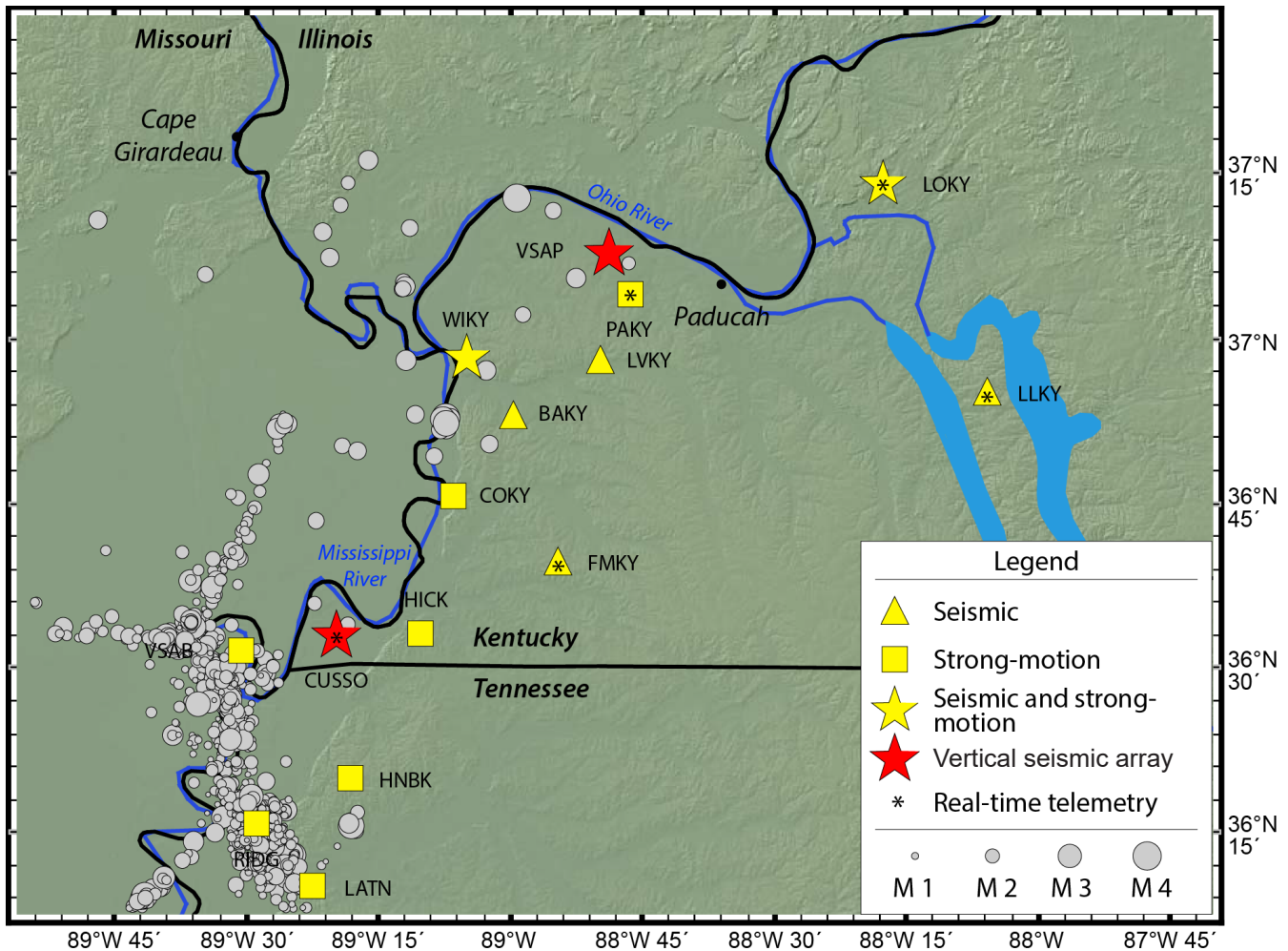


Figure 2. Locations of earthquakes occurring in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017. Kentucky Seismic and Strong-Motion station VSAP is located at the plant.

est to the plant was the magnitude-3.5 event that occurred May 1, 2016, approximately 20 km to the northwest in Ballard County. Figure 3 shows three orthogonal-component recordings from nearby station VSAP (17 km away) and PAKY (24 km away), and the peak ground accelerations recorded at both sites.

Analysis of CUSSO and VSAP Data

The vertical seismic and strong-motion array at CUSSO was functional intermittently between 2009 and 2012; it recorded many local, regional, and distant events (Woolery and others, 2016a, b). Figure 4 shows the history of instrument operations and recorded earthquakes at CUSSO. All the records from CUSSO were checked and corrected to ensure data quality (Woolery and others, 2016a, b). Some preliminary analysis was also conduct-

ed on the records (Woolery and others, 2016a, b). VSAP was relocated to outside the perimeter of the Paducah Gaseous Diffusion Plant for security reasons in 2004 and was in operation until 2014, when the borehole accelerometers stopped functioning because of age. Table 4 lists the records from VSAP that were checked and corrected.

The data from CUSSO and VSAP have been used to study seismic-wave propagation and site effects (Rong and others, 2017; Carpenter and others, in review). Figure 5 shows the mean spectral ratio of S-waves between the surface and bedrock (TF_T), horizontal-to-vertical ratio (HVS_R) of S-waves at the surface (HV_S), and theoretical Thomson-Haskell SH-wave transfer functions (TH_{SH}) at VSAP (left) and CUSSO (right). As shown in the figure, the theoretical transfer function is very

Table 3. Earthquakes of magnitude 3.0 and greater in the vicinity of the Paducah Gaseous Diffusion Plant between January 2013 and December 2017 (from Figure 2).

<i>Magnitude</i>	<i>Date</i>	<i>Time (UTC)</i>	<i>Latitude (°N)</i>	<i>Longitude (°E)</i>	<i>Depth (km)</i>	<i>Location</i>
3.3	08/12/2013	21:43:24.30	36.261	-89.301	4.4	Obion, Tenn.
3.1	04/07/2014	06:24:12.92	36.216	-89.410	6.3	Ridgely, Tenn.
3.1	05/15/2014	15:44:58.34	36.558	-90.020	5.6	Malden, Mo.
3.1	02/28/2015	23:08:44.45	36.536	-89.639	13.4	Lilbourn, Mo.
3.0	11/25/2015	07:08:53.12	36.538	-89.601	8.7	Lilbourn, Mo.
3.5	05/01/2016	06:12:10.03	37.214	-88.988	16.3	La Center, Ky.
3.0	07/05/2016	04:51:13.02	36.151	-89.697	9.0	Caruthersville, Mo.
3.4	09/09/2016	13:45:37.56	36.453	-89.535	10.3	Tiptonville, Tenn.
3.3	11/24/2016	01:57:37.58	36.155	-89.693	8.8	Caruthersville, Mo.
3.6	3/15/2017	16:51:10.09	36.882	-89.123	8.4	Wickliffe, Ky.
3.2	3/19/2017	14:25:12.57	36.880	-89.128	12.2	Bardwell, Ky.
3.0	5/14/2017	12:56:24.05	36.564	-89.599	13.6	Lilbourn, Mo.
3.3	05/16/2017	10:21:52.24	36.873	-89.122	9.1	Bardwell, Ky.
3.0	07/31/2017	02:16:19.62	36.306	-89.490	4.8	Ridgely, Tenn.
3.2	08/18/2017	15:18:21.07	36.447	-89.592	12.6	Portageville, Mo.

similar to the observed transfer function (TF_T); it also shows that the S-wave HVSR is very similar to the observed transfer function. These results suggest that a 1-D theoretical model (transfer function) provides a good approximation of site effect, and the S-wave HVSR could be used as an empirical transfer function of site effect.

Seismic-Hazard Assessment and Communication

New Madrid Active Faults

Although the New Madrid Seismic Zone has been and continues to be intensely studied, the locations of active faults within the zone remain uncertain. As shown in Figure 6, the U.S. Geological Survey postulated five alternative locations for the New Madrid faults in its 2008 and 2014 national seismic-hazard maps (Petersen and others, 2008, 2014). Thus, more accurate determination of fault locations in the zone is important for seismic-hazard assessments in western Kentucky. Edward Woolery and his students at the University of Kentucky have been working with researchers at the University of Memphis to better determine these fault locations using both geologic and geophysical field investigations (Pryne and others, 2013; Van Arsdale and others, 2013; Woolery and Almayahi,

2014; Greenwood and others, 2016; Rucker, 2017). As shown in Figure 7, the seismicity and subsurface geologic features clearly indicate the location of the Reelfoot Thrust Fault.

Pryne and others (2013) acquired two exploratory seismic walkaway soundings (MP-35 and MP-80) (Fig. 8) across the northern boundary of a 30 km × 7.2 km stratigraphic uplift in the northeastern vicinity of the New Madrid North Fault to look for evidence of genesis (i.e., neotectonic or fluvial) (Fig. 9). The previously unknown uplift, which Pryne and others (2013) called the Charleston Uplift, was discovered using 520 electric logs from shallow (100 m) lignite exploration wells and geospatial stratigraphic mapping. Although there are no known surface faults bounding this feature, Pryne and others (2013) hypothesized that the more than 30 m of structural amplitude exhibited in the mapping of Quaternary and Tertiary horizons based on well logs had a tectonic origin. The two seismic soundings were performed north of and within the uplift to further test this hypothesis. Results indicate 47 and 60 m of relief across the tops of the deeper Cretaceous and Paleozoic horizons, respectively (Fig. 9). A subsequent University of Kentucky master's thesis by Rucker (2017) used an additional 18 seismic soundings and one ground-penetrating-radar profile to confirm Paleozoic

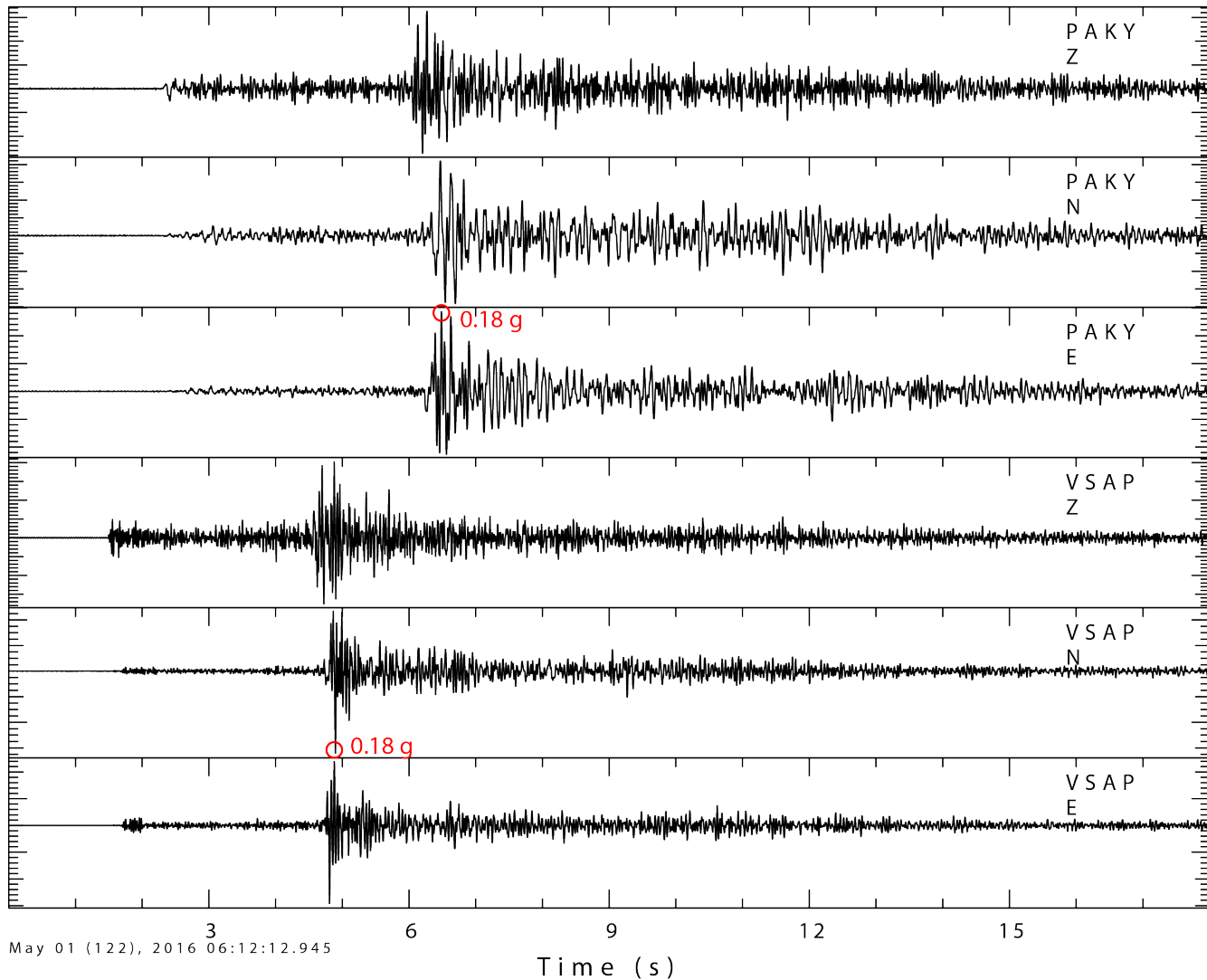


Figure 3. Example recordings by the seismic-monitoring network. Three-component recordings of the May 1, 2016, magnitude-3.5 earthquake near La Center, Ky., from VSAP (17 km away) and PAKY (24 km away). Peak ground accelerations (acceleration due to gravity) are labeled.

and Cretaceous offset across the boundaries of the uplift, and better constrain the surface projection of the uplift (Fig. 10). Results from Rucker's thesis (2017) confirm Paleozoic and Cretaceous offset throughout the uplift, as well as indicate that the preliminary boundaries proposed by Pryne and others (2013) are appropriate. The N46°E trend of the uplift, as well as its coincidence with contemporary microseismicity, suggest that this feature may be related to the New Madrid Seismic Zone, specifically the New Madrid North Fault.

Ground-Motion Attenuation

The ground-motion attenuation relationship, also known as the ground-motion prediction equation, is an important parameter for seismic-hazard assessment. The GMPE for the western United States was developed from ground-motion observations along the West Coast, California in particular (Joyner and Boore, 1981). In contrast, GMPEs for the central and eastern United States are developed either solely from computer simulations or from computer simulations with limited observations of small to moderate earthquakes ($M < 6.0$). For example, Atkinson and Boore (2006) developed a GMPE from synthetic records based on stochastic

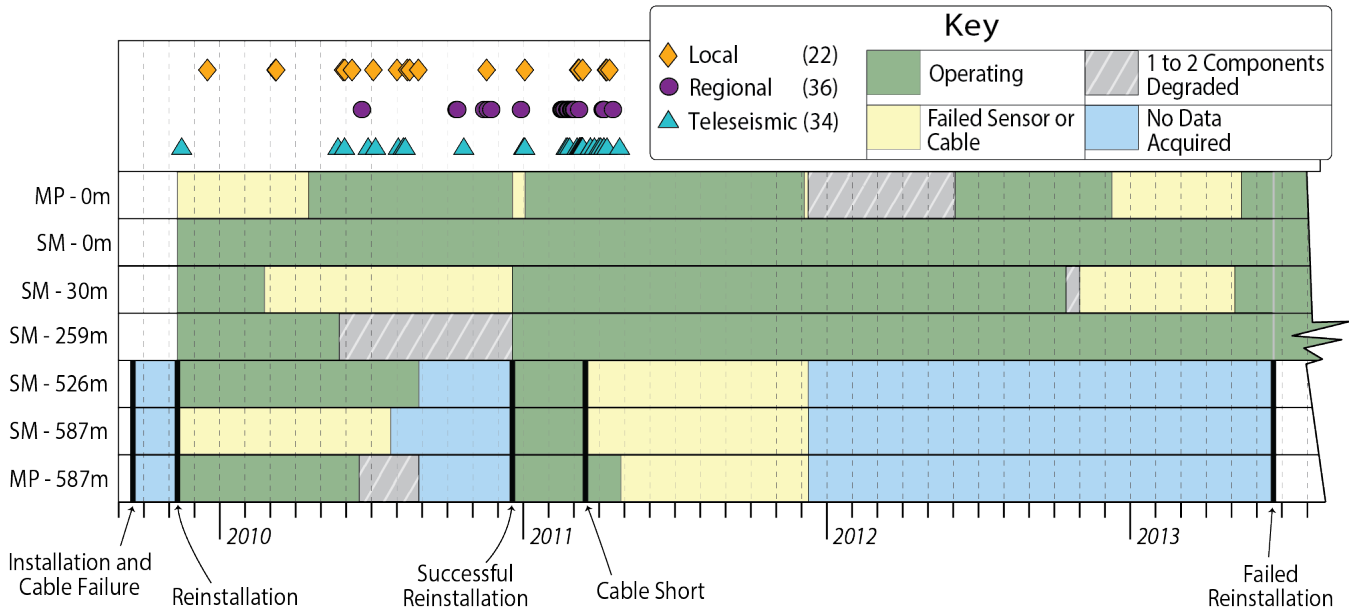


Figure 4. Summary of CUSSO's operational history. MP=median-period seismic sensor. SM=strong-motion sensor. Numbers beside MP and SM are sensor depths below the surface in meters.

Table 4. Earthquakes recorded at station VSAP between 2004 and 2014.

Date	Time (UTC)	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude	Distance (km)
05/01/2005	12:37	35.83	-90.15	10.0	4.2	187
06/02/2005	11:35	36.15	-89.47	15.0	4.0	124
06/20/2005	02:00	36.39	-88.99	7.7	2.7	27
06/20/2005	12:21	36.92	-89.00	18.7	3.6	28
06/27/2005	15:46	37.63	-89.42	9.6	3.0	77
01/02/2006	21:48	37.84	-88.42	7.3	3.6	86
04/18/2008	09:36	38.45	-87.89	14.2	5.2	168
04/18/2008	15:14	38.46	-87.87	15.5	4.7	169
04/21/2008	05:38	38.45	-87.88	18.3	4.0	168
03/02/2010	19:37	36.79	-89.36	8.2	3.7	61

finite-fault simulations. Thus, GMPEs for the central and eastern United States need to be refined by ground-motion observations, in particular from large ($M > 7.0$) earthquakes.

The 2008 Wenchuan, China, earthquake ($M 7.9$) occurred along the Longmenshan Fault (Burchfiel and others, 2008), which is located on the western border of the South China stable continental region. Although the Wenchuan area is different from the central United States, the eastern part of it, the Sichuan Basin, is located in a stable continental region (Fig. 11) that is similar to the central and eastern United States (Wheeler, 2011). Thus, ground motions from the Wenchuan earthquake could be

used to constrain GMPEs for the central United States; a preliminary comparison (Wang and Lu, 2011) suggested using the Wenchuan ground motions was appropriate. A detailed study compared GMPEs developed for the central United States with the one developed from the Wenchuan earthquake (Feng and others, 2015). Figure 12 compares GMPEs for the central United States (Somerville and others, 2001; Silva and others, 2002; Campbell, 2003; Atkinson and Boore, 2006; Pezeshk and others, 2011) with the one developed from the Wenchuan earthquake (Feng and others, 2015). The results show that most of the ground-motion attenuations

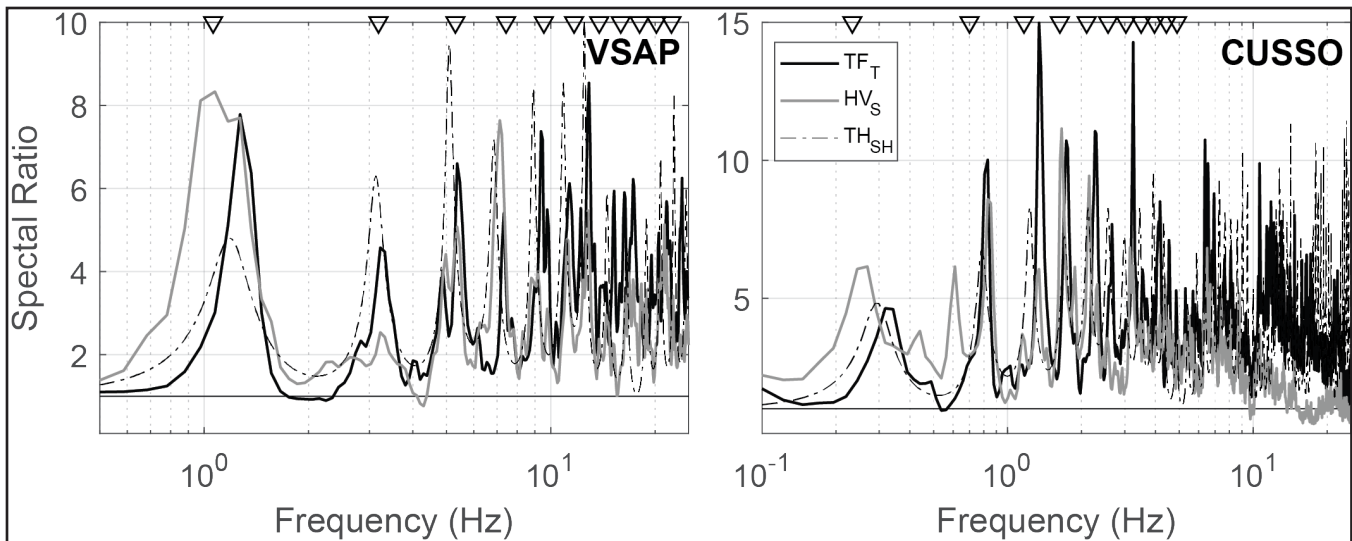


Figure 5. Mean spectral ratios from recordings at VSAP (left) and CUSSO (right), and theoretical Thomson-Haskell SH-wave transfer functions. TF_T and HV_S are surface-to-bedrock and surface horizontal-to-vertical spectral ratios, respectively. TH_{SH} is the theoretical SH-wave transfer function. Inverted triangles show the SH-wave resonance modes predicted for each soil column.

for the central and eastern United States are similar to that for the Wenchuan area, except for the Atkinson and Boore GMPE (2006), which is significantly different at near-source distance. Thus, KGS used ground-motion data obtained from the Wenchuan

earthquake to develop a GMPE for the central and eastern United States.

Seismic-Hazard Assessment

In order to improve understanding and communication about ground-motion hazards in the central United States, KGS participates in workshops and holds discussions with the U.S. Geological Survey and other federal and state agencies about related issues. In July 2013, KGS provided an official comment on the 2014 national seismic-hazard maps. Zhenming Wang, Edward Woolery, and Seth Carpenter attended and gave presentations at a workshop, “CEUS Earthquake Hazards Research Review and Planning,” Feb. 25–26, 2014, in Memphis, Tenn. Zhenming Wang participated in the Applied Technology Council/USGS Seismic Hazard User-Needs Workshop, Sept. 21–22, 2015, in Menlo Park, Calif., and gave a presentation, “The USGS National Seismic Hazard Mapping Project: Issues and Improvements.” On Jan. 27, 2017, KGS and USGS staff met in Lexington, Ky., with representatives of the Structural Engineers Association of Kentucky and the state’s Division of Solid Waste. The participants agreed that the New Madrid Seismic Zone poses a significant hazard to western Kentucky and that scenario-based seismic-hazard analysis can help convey the consequences of a major New Madrid earthquake to nonspecialists; however, the scenarios are limited because

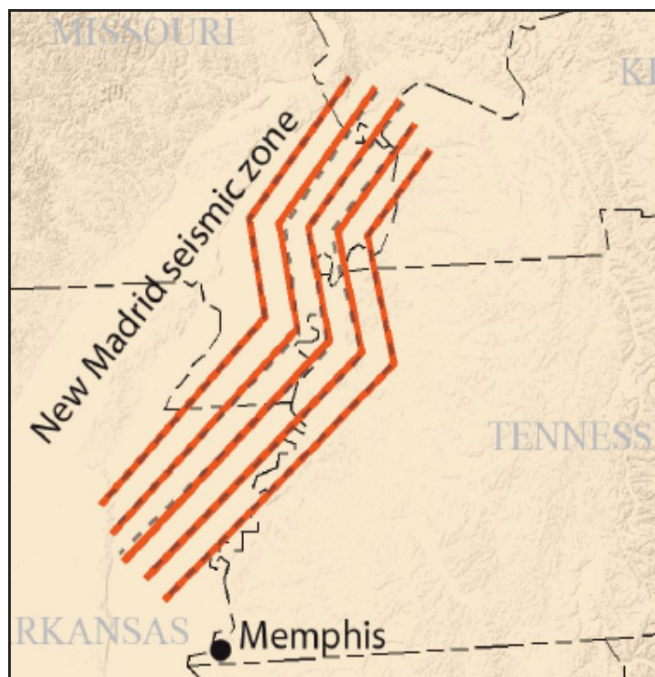


Figure 6. Locations of the active faults in the New Madrid Seismic Zone used in the USGS national seismic-hazard maps (Petersen and others, 2008, 2014). Dashed black lines are from the 2008 update, and the solid orange lines are from the 2014 update.

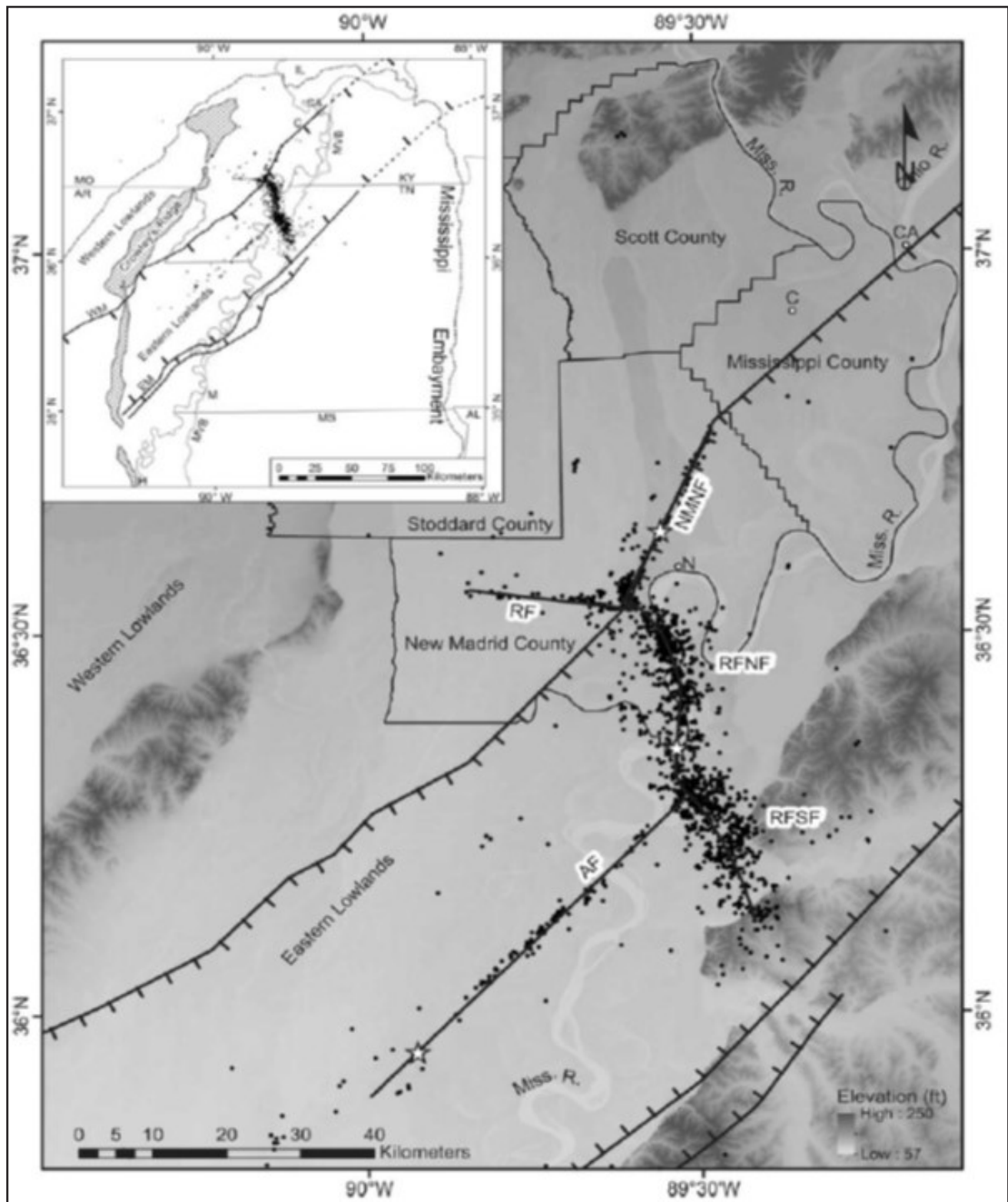


Figure 7. Seismicity (black dots), active faults (black lines), topography (grayscale background), and geologic features in the New Madrid Seismic Zone. AF=Axial Fault (Cottonwood Grove Fault). NMNF=New Madrid North Fault. RF=Reelfoot Fault. RFNF=Reelfoot North Fault. RFSF=Reelfoot South Fault. From Van Arsdale, R., Pryne, D., and Woolery, E., 2013, Northwestern extension of the Reelfoot North Fault near New Madrid, Missouri: *Seismological Research Letters*, v. 84, p. 1114–1123, doi:10.1785/0120120241. © Seismological Society of America.

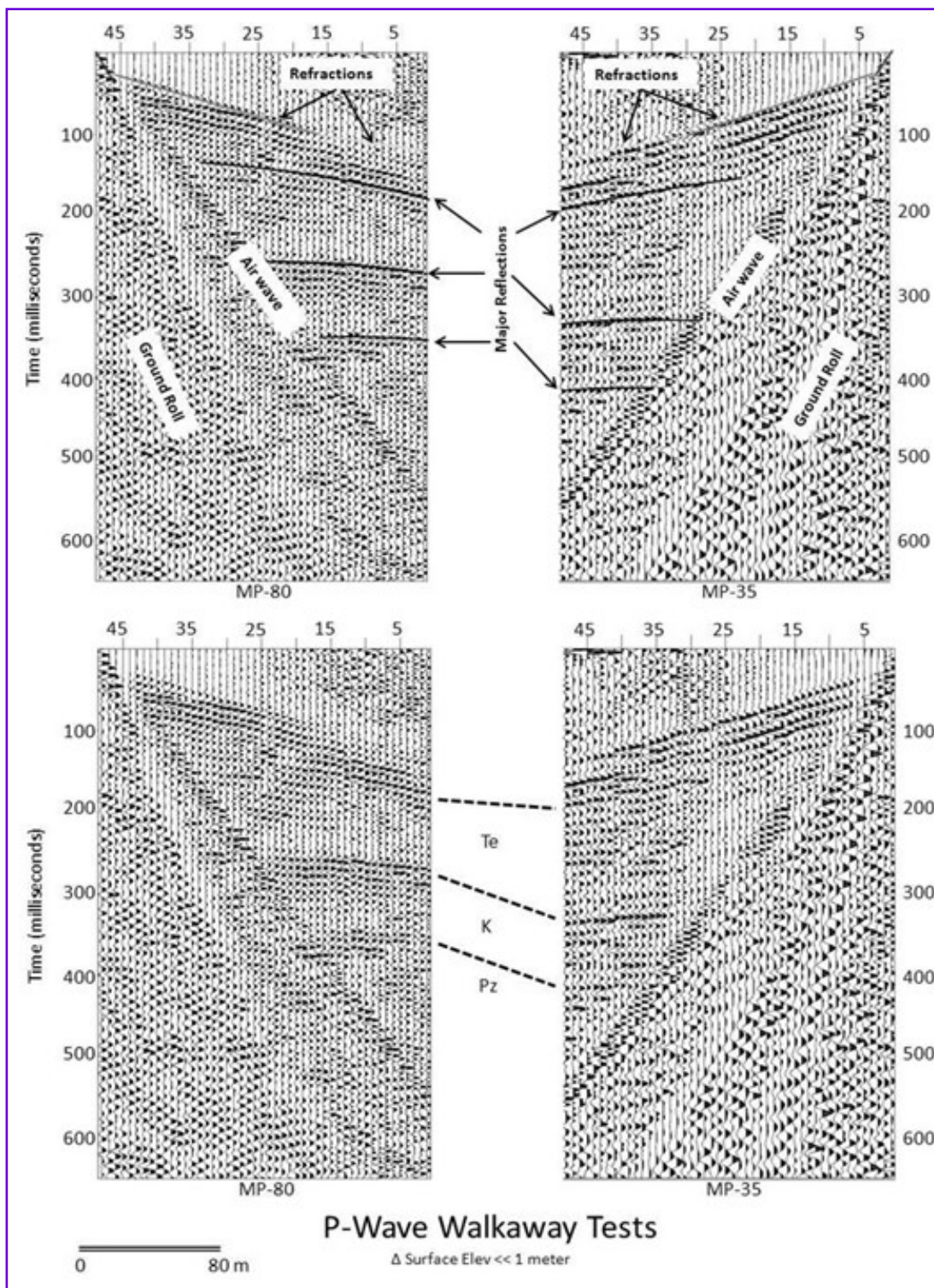


Figure 8. Two seismic-reflection soundings, MP-35 and MP-80, collected north of the Charleston Uplift and within the uplift, respectively. (top) Coherent phases, including ground roll, air wave, direct wave/refractions, and three significant reflections. (bottom) The two most prominent deeper reflections on both profiles are the tops of the Cretaceous (K) and Paleozoic (Pz) horizons. Relief across the K and Pz between the sites is 47 and 60 m, respectively. Approximately 19m of relief is calculated across the Tertiary horizon. From Pryne, D., Van Arsdale, R., Csontos, R., and Woolery, E., 2013, Northeastern extension of the New Madrid North Fault, New Madrid Seismic Zone, central United States: *Bulletin of the Seismological Society of America*, v. 107, p. 2277–2294, doi:10.1785/0120120241. ©Seismological Society of America.

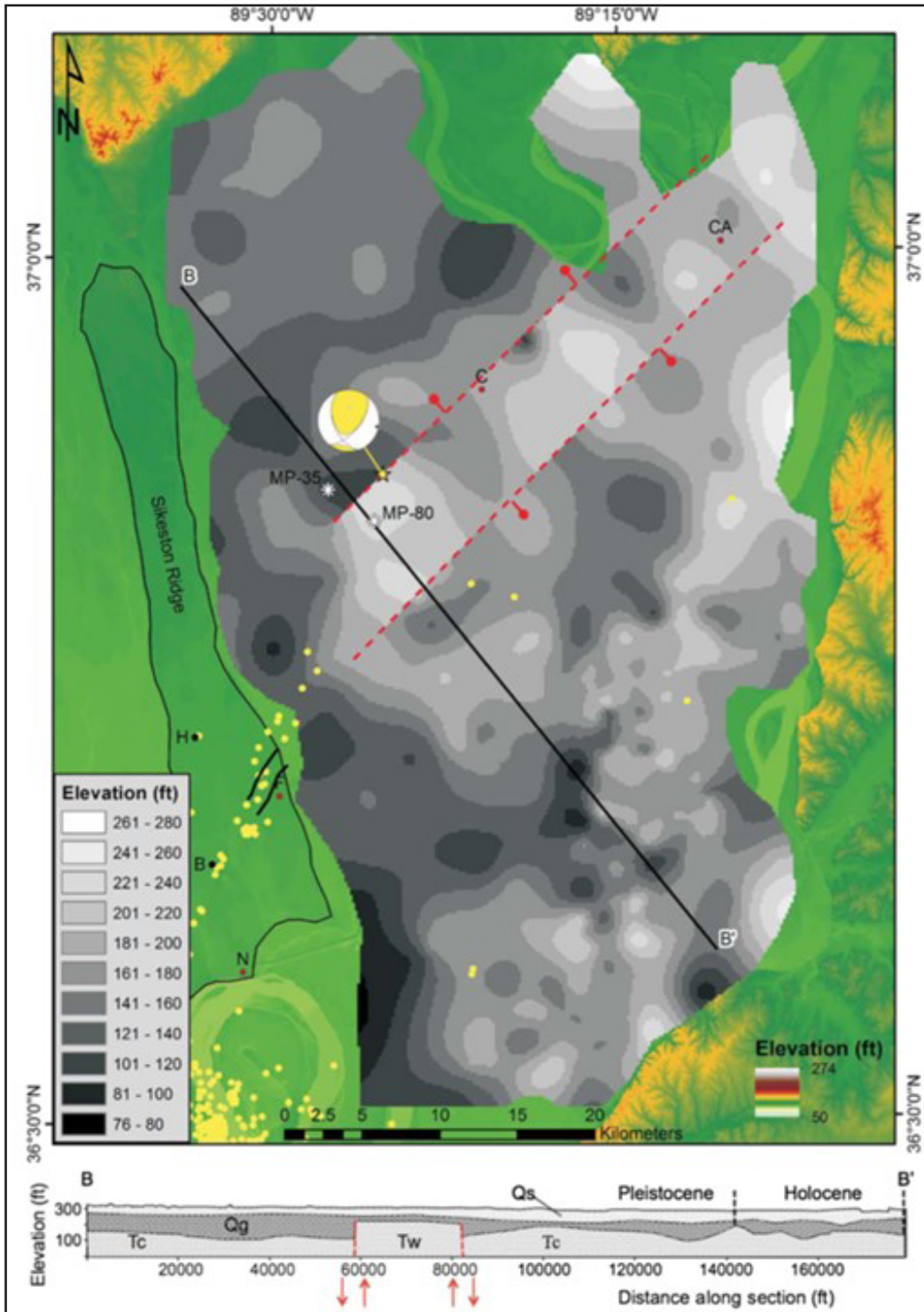


Figure 9. Top of the Paleogene (bottom of Quaternary Mississippi River gravel) structure contoured as separate surfaces, south, within, and north of the Charleston Uplift, and cross section B–B'. Location of the Feb. 21, 2012, earthquake and interpreted faults (represented by red lines with barbs on downthrown side). Red dots=wells. Contour interval=6 m. C=Charleston. CA=Cairo. F=Farrenburg. N=New Madrid. Qs=Quaternary alluvial sand/silt/clay. Qg=Quaternary gravel. Tc=Tertiary Claiborne Formation. Tw=Tertiary Wilcox Group (Flour Island Formation). Cross section B–B', vertical exaggeration X40. Modified from Pryne, D., Van Arsdale, R., Csontos, R., and Woolery, E., 2013, Northeastern extension of the New Madrid North Fault, New Madrid Seismic Zone, central United States: *Bulletin of the Seismological Society of America*, v. 107, p.2277–2294, doi:10.1785/0120120241. © Seismological Society of America.

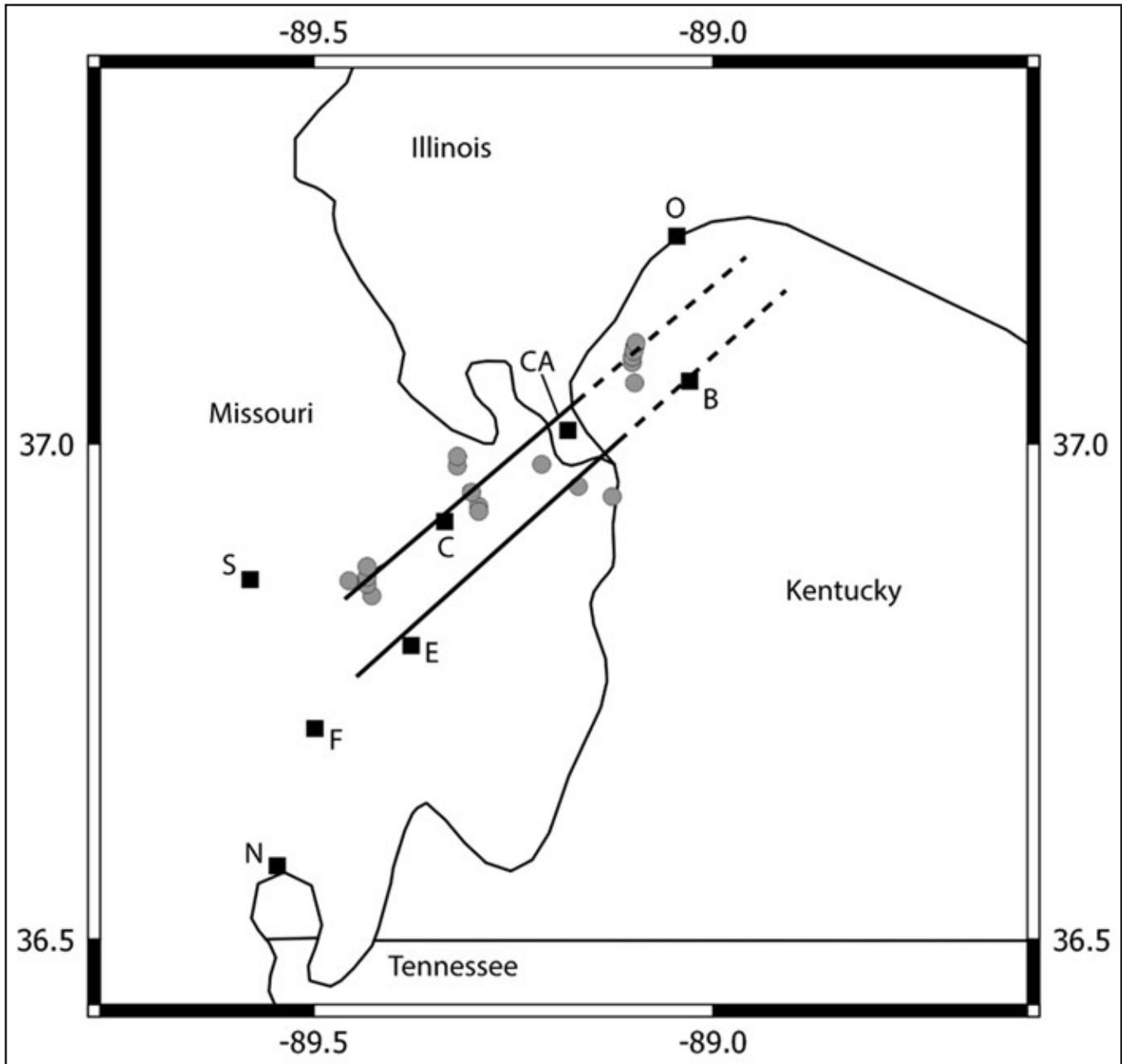


Figure 10. Charleston Uplift and field locations. Solid lines are the boundaries of the uplift from Pryne and others (2013). Dashed lines are the northeastward, straight-line projection of those boundaries into western Kentucky. Gray circles are field sites for seismic sounding. Black squares are population centers in the region: B=Barlow, Ky.; CA=Cairo, Ill.; C=Charleston, Mo.; E=East Prairie, Mo.; F=Farrenburg, Mo.; N=New Madrid, Mo.; S=Sikeston, Mo.; O=Olmsted, Ill. From Rucker (2017).

they cannot seamlessly incorporate uncertainties. KGS's policy is that probabilistic seismic hazard analysis (PSHA) is a valid method, although there may be disagreements among professionals regarding input data and details of the calculations.

KGS also conducts scenario-based seismic-hazard analyses and communicates the results to stakeholders. Figure 13 shows the mean peak

ground acceleration for Kentucky from a scenario earthquake of M7.5 in the New Madrid Seismic Zone (Carpenter and others, 2014). Orton (2014) conducted scenario-based hazard analysis on a series of earthquakes in the New Madrid Seismic Zone; her results are summarized in Orton and others (2016) and Wang and others (2016). KGS also used scenario-based seismic-hazard analysis

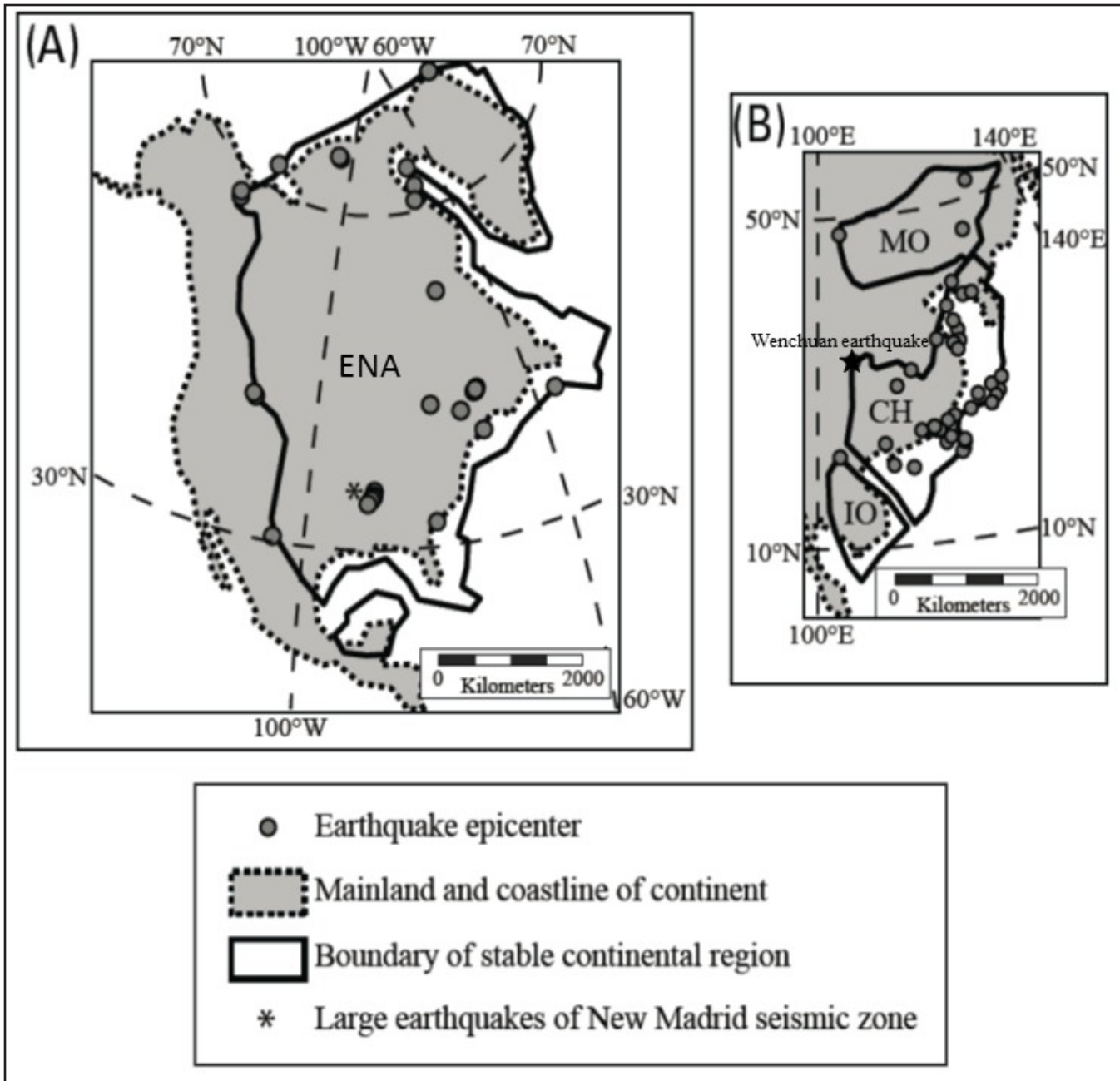


Figure 11. Stable continental regions of North America (A) and South China (B). Star=Wenchuan region. ENA= eastern North America stable continental region. CH= eastern China stable continental region. MO= Mongolia stable continental region. IO= Indochina stable continental region. Modified from Wheeler, R.L., 2011, Reassessment of stable continental regions of Southeast Asia: *Seismological Research Letters*, v. 82, p. 971–983, doi.org/10.1785/gssrl.82.6.971. ©Seismological Society of America.

to provide potential ground-motion hazards for a small induced earthquake in eastern Kentucky (Wang and others, 2017).

Potential Loss Estimate and Mitigation Policy

Orton (2014) simulated potential losses for 36 scenario earthquakes with magnitude between

7.1 and 8.2 and focal depths of 10 and 20 km in the New Madrid Seismic Zone using the Federal Emergency Management Agency's Hazus-MH software (www.fema.gov/hazus-software; last accessed 01/15/2019). She also interviewed businesspeople, public officials, and other professionals in western Kentucky whose occupations are associated with

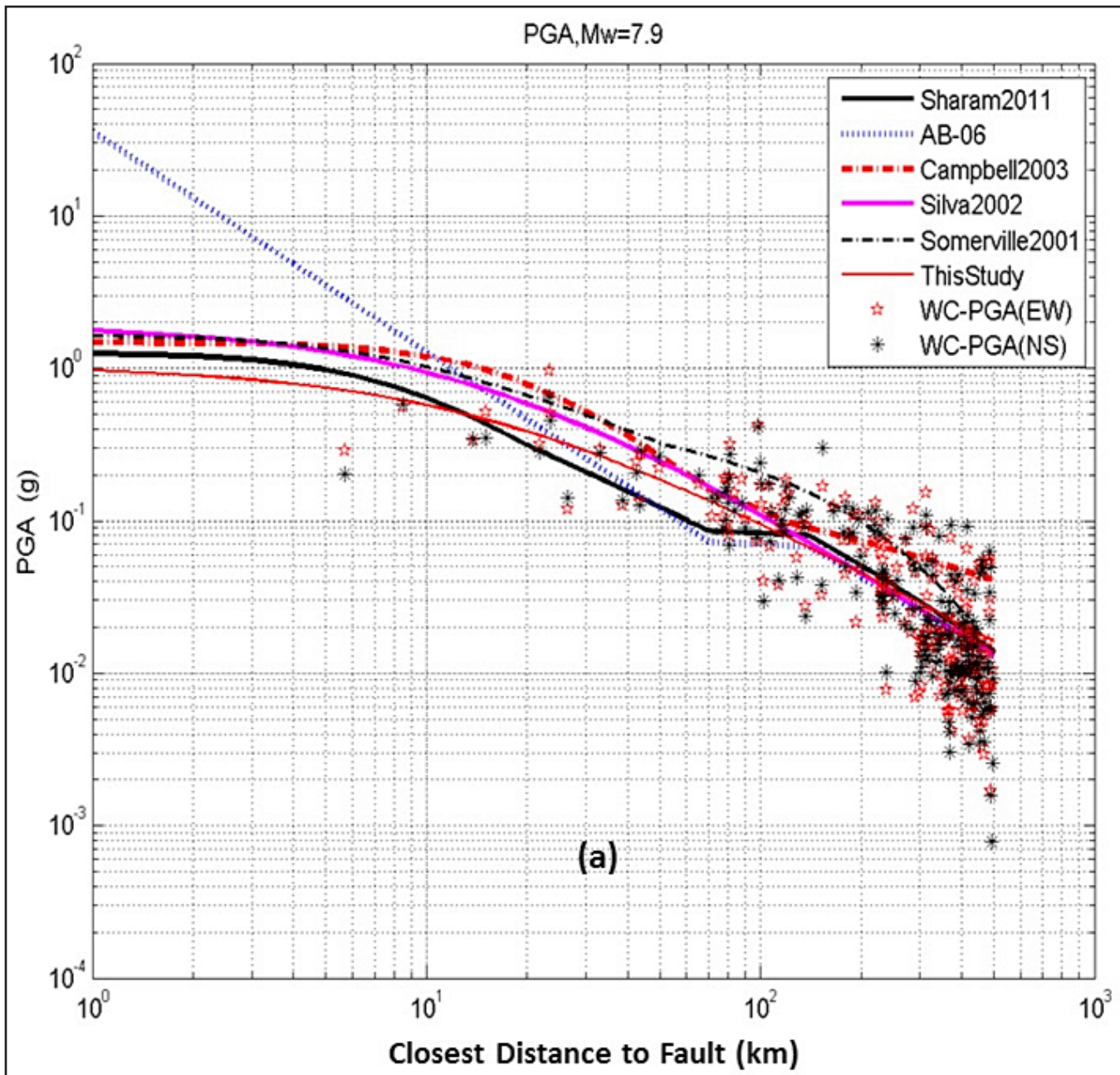


Figure 12. Comparison of ground-motion predictions for the Sichuan Basin and four GMPEs for the central and eastern United States for an M7.9 earthquake (Feng and others, 2015). Sharam2011 from Pezeshk and others (2011). AB-06 from Atkinson and Boore (2006). Campbell2003 from Campbell (2003). Silva2002 from Silva and others (2002). Somerville2001 from Somerville and others (2001).

seismic mitigation in order to understand the perceived impacts of seismic-hazard assessment and resulting mitigation policies on economic development (Orton, 2014; Orton and others, 2016). The simulation results given in Orton (2014) showed that large uncertainties are inherent in the estimation of earthquake parameters, ground-motion values in particular, for the New Madrid Seismic

Zone. Table 5 compares the maximum ground motions between the three scenario events simulated by Orton (2014), the observed values from the Wenchuan, China, earthquake, and probabilistic seismic-hazard analysis estimates by the U.S. Geological Survey for the New Madrid Seismic Zone (Petersen and others, 2014).

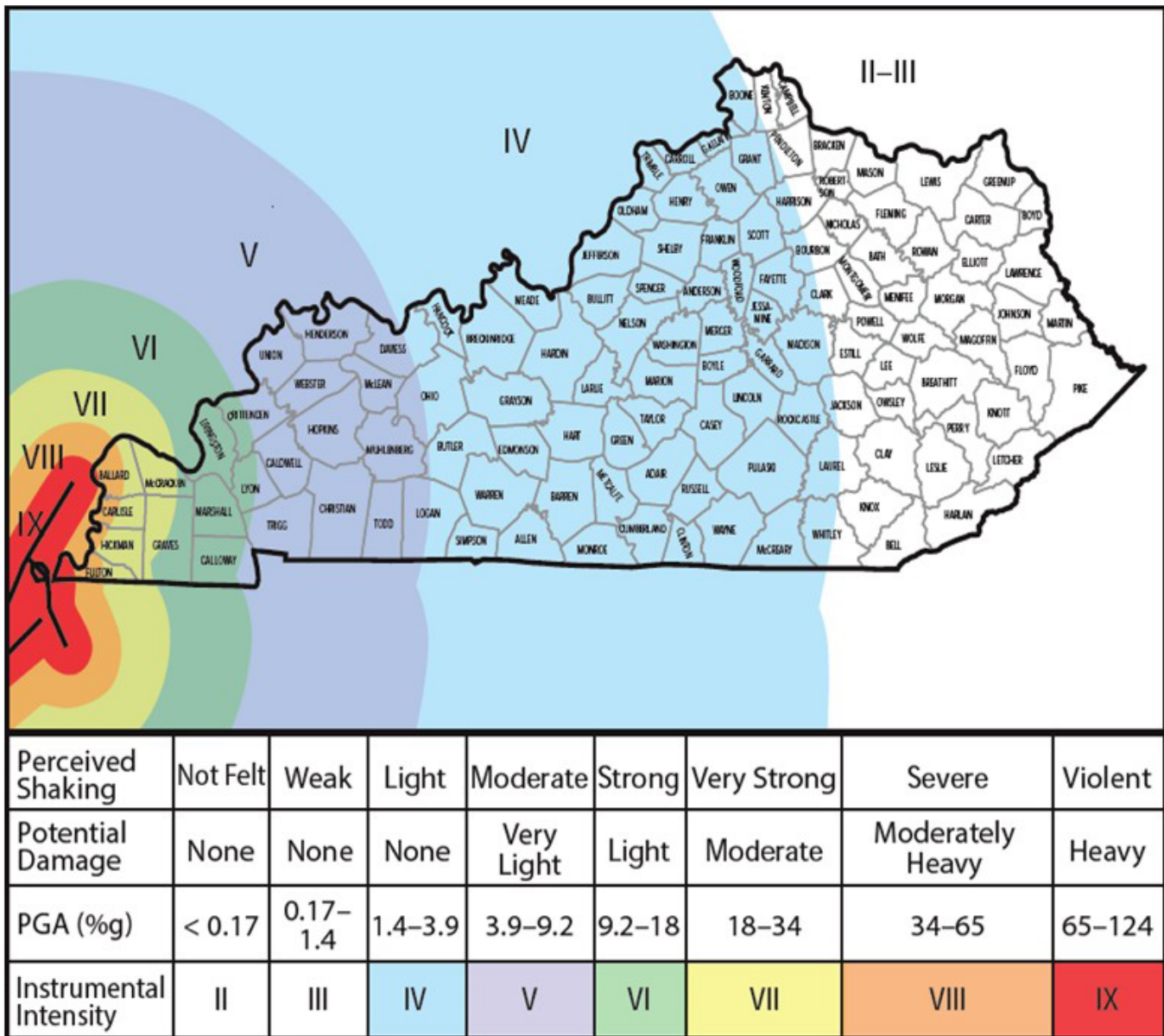


Figure 13. Predicted peak ground acceleration, in percentage of the acceleration of gravity, on hard rock (average shear-wave velocity is greater than 1,500 m/s) from a magnitude-7.5 scenario earthquake in the New Madrid Seismic Zone. From Carpenter and others (2014).

Table 5. Comparison of maximum ground motions for New Madrid scenario earthquakes. From Orton and others (2016). PGA=peak ground acceleration. SA0.3=0.3s response acceleration. SA1.0=1.0s response acceleration.

Model ID	Maximum PGA (g)	Maximum SA0.3 (g)	Maximum SA1.0 (g)
A 4026 82 10/20 (M8.2)	3.308	5.263	5.839
C 4027 71 10/20 (M7.1)	1.447	1.983	1.628
SW Fault 1 (M7.7)	1.100	1.380	1.140
Wenchuan (M7.9)	0.950	2.370	0.360
national seismic hazard maps (2 percent in 50 yr)	1.960	3.520	1.690

Orton's (2014) study also showed that the national seismic-hazard maps and resulting mitigation policies, such as building and residential codes, were perceived by her interview subjects to have adverse impacts on economic development in Kentucky, western Kentucky in particular; she did not perform a rigorous benefit-cost analysis to evaluate the possible value of stricter standards in reducing losses should a major New Madrid earthquake occur, however.

Summary

From January 2013 to December 2017, KGS continued to monitor earthquakes and conduct research on seismic hazards in the vicinity of the Paducah Gaseous Diffusion Plant. Fifteen earthquakes with magnitude greater than 3.0 occurred in the vicinity of the plant during this period. We improved our understanding of seismic-wave propagation through thick sediments and ground-motion site effects using data collected from CUSSO and VSAP. We also improved our understanding of fault locations in the New Madrid Seismic Zone, ground-motion attenuation in the central United States, and seismic-hazard assessment. The data will contribute to the development of design ground motions for western Kentucky, and specifically for buildings and facilities at the Paducah Gaseous Diffusion Plant.

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